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Research advance in failure risk and local strength failure for high arch dams

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To develop national economy and use the water resources and hydropower resources sufficiently, a lot of high arch dams, with the height of more than 200 m, have been and will be built in China. Although arch dams have good mechanical behavior, there is still failure possibility due to the huge water pressure and high stress level in dam, complex topographic and geologic conditions, formidable environment and high intensity earthquake. As one of the three main aspects concerning the safety of high arch dam, the study on global destruction, has been elaborated in the literatures, and research advance in the other two aspects, namely the failure risk and local damage of high arch dams, will be reviewed in this paper. In recent years, the failure risk of high arch dams has been investigated, and the model for identifying dam failure risk factors has been established. It is shown that the foundation deterioration and strong earthquake are the major risk sources for high dam failure. With the fault tree method, the failure mode and failure probability of high arch dams are studied, and the principle for determining failure mode and the method of calculating failure probability are proposed. Meanwhile, the determination principle of acceptable risk standard for high arch dam was proposed, and the acceptable risk rate and the acceptable standard value of various risk losses were given. For the local damage of arch dam, it is pointed out that the local damage belongs to the strength failure at material level. The study on local failure mechanism of arch dam is reviewed, based on the theories that from traditional strength theory to damage mechanics and meso-mechanics theory. Aiming at the cracking, the main pattern of local failure of high concrete dam, the research advances in the analysis methods and cracking criteria for smeared crack model and discrete crack model are summarized, and the research findings of preventive measures for local failure are shown.

high arch dam, failure risk, local damage, research advance

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To develop national economy, to save energy and to reduce emission, exploitation and utilization of water resources and hydropower resources are continued in China. At present, the height of arch dams under construction and to be built are of 300 m high level, such as Jinping arch dam (305 m high), Xiaowan arch dam (294.5 m high), Xiluodu arch dam (285.5 m high), and Baihetan arch dam (289 m high). The construction scale and difficulty of these dams are beyond the current design specifications, and there is hardly successful precedential reference. Moreover most of these high arch dams are located in the western region of China, where the topographic and geologic conditions are quite complex, with harsh environment and high seismic intensity as well as frequent geological disasters. In addition the resistance of dam and foundation may be reduced due to the construction quality and environment change. All of these have seriously threatened the safety of high arch dams. Once a high dam fails, catastrophic tragedy would happen and lives would be lost. Therefore, the failure and safety of high arch dam have become a public safety issue. Since the 1980s, the researchers and engineers in China have carried out in-depth research systemically and obtained a large number of innovative results for the high arch dam construction. The level of the results is in the leading position all over the world.

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1 High arch dam failure modes and failure risk

Arch dam is a high order statically indeterminate three-dimensional structure, which has good mechanical properties, great overload capacity and high safety. But due to huge loads, high stress levels, complex topographic and geologic conditions, harsh environment and high seismic intensity, some operating arch dams still fail. In December 1959, Malpasset arch dam in France suddenly broken, which killed more than 500 people and caused property losses amounting to 30 billion francs, and the important reason was the low shear strength of the left bank skewback caused by the poor rock mass quality, cranny development and containing mud. Before the accident, heavy rain had continued for 29 days, with rainfall up to 490 mm, which led to further deterioration of the dam foundation rock mass. The Pacoima arch dam in U.S. suffered earthquakes with magnitude 6.6 twice in 1971 and 1994, although the dam itself was not significantly damaged, the joint between left dam abutment and thrust block was opened. After the joint was opened for about 6.4–9.7 mm in the first earthquakes, 35 prestressed anchors of 3087 kN were used for reinforcing. After the second earthquake, the joint was opened for another 47 mm, and parts of the prestressed anchors were ruptured. On October 9 1963, a landslide took place in the upstream reservoir bank of Italy Vaiont arch dam, whose height is 262 m, a 300 million cubic meters of rock mass glide into the reservoir at high speed, and 50 million cubic meters of water was extruded, which destroyed a city and several towns, and the underground powerhouse was destroyed by the air shock wave. About 3000 people died in the accident.

At present, dam safety evaluation is mostly based on the specification method [1,2] and modern numerical method, such as finite element method [3–6]. These methods are conducted with specified failure approach, and the probability of failure is not involved as well as the research on failure mode, which results in a lot of artificiality in analysis. In addition, the allowable safety degree and the potential losses are not combined so that the balance between safety and economy cannot be considered, and the safety of structure is checked only from the technical perspective [7,8].

Risk analysis is to study the system risk when it completes its intended function under certain conditions, including system accident probability and consequence determination. For risk analysis, the safety evaluation has to analyze the risk source, failure mode and failure probability, and to estimate the risk of loss. At present, risk analysis of water conservancy is focused on the hydrological risk and hydraulic risk, but there is hardly risk analysis for the structural aspects. The only relevant literatures [9–11] are mainly on the issues of overtopping and instability failure of embankment dam, since the structure and failure mechanism are relatively simple. Risk analysis for concrete dam especially the high arch dam is just in the infancy stage, and its main research results are as follows.

(i) Identification of risk sources. It is shown that the major factors of high concrete dam failure can be divided into internal and external, based on the on-site investigation and data statistical analysis of high concrete dam accidents both at home and abroad. The external factors are the earthquake and subsequent secondary disasters, floods, explosions, which increase the effect on the dam. The internal factors are the unfavorable geological structure in dam foundation, damages and defects in dam body, and material and structural deterioration caused by the long term performance as well as change of environmental conditions, all of which would reduce the bearing capacity of the dam. It can be drawn from both of the measured data and the research of dam failure risk factors [12,13] that flood is the major cause for the embankment dam to break, and there are many achievements about flood risk analysis [14–16]. While the major reasons for high arch dam failure are the foundation deterioration and strong earthquake [17], the related results are lack. Gu and Wang [18] established the dam risk identification ANP model and the dam risk network structure model, by which the priority order of dam failure risk factors can be obtained, and the main risk factors of dam breach can be determined. The ANP model is just suitable for earth rockfill dam, and it is difficult for concrete dam.

(ii) Failure modes and failure probability of high arch dam. According to [19], the possible failure modes of high arch dam can be summarized as: (1) The strength failure of the dam body; (2) buckling of the dam body; (3) destabilization of arch dam along its base surface; (4) slip of the dam abutment rock; (5) global destruction of arch dam and foundation system. The consequence of failure is that the arch dam cannot be in normal operation or lose the carrying capacity. Different failure modes have different failure probabilities, and the specified failure mode is not necessarily the most possible failure mode. In order to find the maximum probability failure mode, Chen and Ren used the fault tree method to study the failure mode and failure probability of high arch dam, under the effect of some kind of risk source, and proposed the principle for determining high arch dam failure mode [20–22] and the calculation method of failure probability [23,24]. However, it is difficult to calculate the failure probability when applying the method because of very few samples of concrete dam break. Jin et al. [25] proposed the improvement of SVM response surface reconstruction method, and combined it with the FORM method and the importance sampling method in reliability analysis; the exact solution of failure probability for some simple structures can be obtained. It is hard to apply the method to dam.

(iii) The research of dam failure risk and acceptable risk. In addition to determining the failure probability, the risk analysis of high arch dam safety is also needed to study the failure loss, including economic loss, life loss, environment and ecology loss and social impact. Because the loss of dam breach risk is fuzzy and the suffered loss area is vast, Gu [26] proposed the fuzzy comprehensive evaluation method and established a fuzzy comprehensive evaluation index system, through which the level of various losses can be determined. Based on the fuzzy matter-element and exponential smoothing algorithm, Wang et al. [27,28] proposed the evaluation method of life loss caused by dam breach and the evaluation method of loss caused by dam breach based on GIS. But the exact risk loss is hardly obtained since it is difficult to calculate quantitatively the environment and ecology loss as well as the social impact.

In order to make the correct safety warning of dam breach, the acceptable risk standard [29] needs to be determined, for which many aspects should be considered comprehensively, such as the characteristics of system, science and technology level, economic development, the value of human life and its recognition degree, as well as the harm scope and degree and other factors. Gu [30] established the comprehensive risk standard determination method based on F-N curved surface, and the acceptable comprehensive risk standard value was given. Chen [31,32] presented the principle of determining high arch dam acceptable risk standard, and the acceptable risk rate as well as the acceptable standard value of various risk losses.

2 High arch dam failure process, mechanism and analysis methods

Existing research [33] shows that the buckling failure of arch dam would generally not happen unless the high strength material is used and the arch ring is very thin. Both numerical simulation and geomechanical model test [34–36] show that since arch dam is a hyperstatic three-dimensional structure, the dam failure generally starts from local damage and cracking, and the area of damage and cracking gradually grows with loading increase or bearing capacity degradation, eventually ends in global destabilization. This is a progressive failure process from local damage to global destruction. Figure 1 shows the growing process of cracking and yield area of Xiaowan high arch dam as the upstream water pressure increases [37]. Some cases of arch dam destruction also illustrate the failure process [12].

It can be concluded that there are two levels in a high arch dam failure: the local damage at material level and the global destruction at structure level. The former is the local cracking, crushing or other damage forms, and the latter represents the loss of carrying capacity. Apparently, they are different, but have some connection. If only the local damage at the material level happens, the dam still has a certain bearing capacity, and can continue service. Only if the damage area expands to a certain extent and the bearing capacity is lost, will the global destruction of the dam occur. The failure mode may be the slip of the abutment rock, or the destabilization of arch dam along its base surface or the global destruction of dam and foundation.

Obviously, the local damage is caused by lack of material strength and it belongs to the strength failure. Whether damaging or not, it can be determined by examining the stress and strength. Although the global destruction of arch dams is called "stability" by almost all the researches, and a lot of analysis methods are developed [4,38–40], they are still in the frame of strength failure in essence, and analysis on global destruction is still based on the strength theory. Ren pointed out that the global failure of arch dam is a stability problem and it is the extreme point destabilization according to the character that the load-displacement curve obtained in failure process possesses an extreme point. Hence the global destruction of arch dam is a physical instability which starts from strength failure, and the instability is due to the nonlinearity existing in the relation of stress and strain. Therefore, the global destruction analysis of high arch dam should be based on the stability theory of mechanical system, and the corresponding analytical method and failure criterion can be obtained through establishing and solving the physical disturbance equation. This has been elaborated in several articles of Ren [35,37,41] and would not be discussed here. The key point will be focused on the local damage of high arch dam.

3 Local damage of high arch dam

High arch dams are made up of concrete, rock and the rock joints, which are mostly brittle materials with low or no tensile strength. Different from middle and low-height arch dams, both the tensile stress and the compression stress are considerable large in high arch dam, so it is more likely to be damaged under loading. This is not allowable in the current design codes. Many researches have been done on this issue. In what follows, the research advance will be stated in three aspects respectively, namely the local damage mechanism, the analysis methods with corresponding criterion, and some prevention measures.

3.1 The damage mechanism of dam concrete and foundation rock

Cracking, shear and compression failures are the common patterns in dam concrete and foundation rock. These failures are part of strength failure at material level, and they are mostly caused by excessive stress values. The failure mechanism has been studied from different perspectives with various theories and methods.

(i) Study on local damage based on traditional strength theory. In the context of traditional strength theory, material is considered to be failed if the maximum principle stress exceeds the material strength. This is a uniaxial strength theory. But the reality and experiments show that the actual strength is different from the uniaxial strength

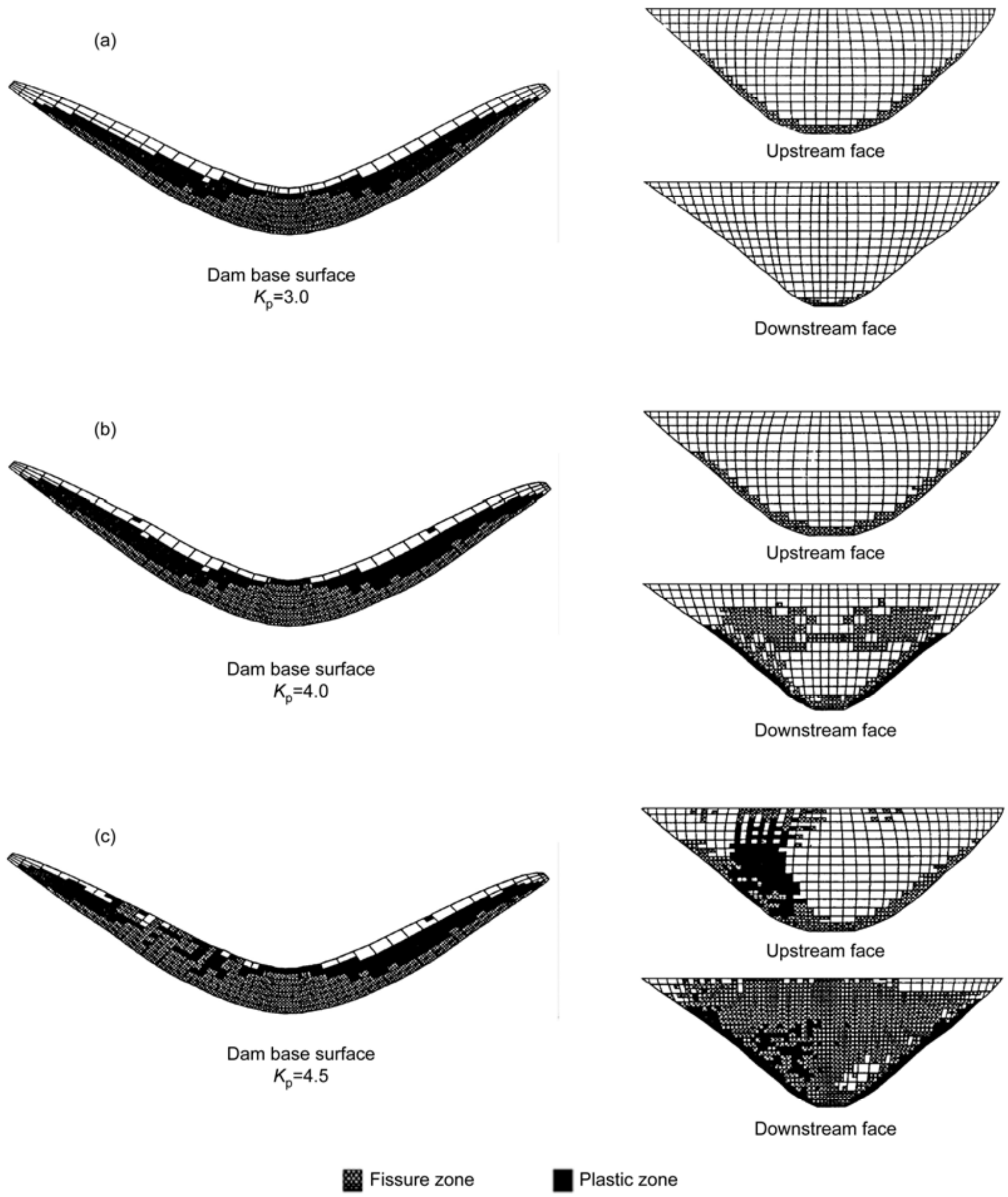

Figure 1 Destruction region in upstream, downstream and base surfaces of Xiaowan arch dam.

and there are multiple failure patterns when the material is in a complex stress state. This implies that the traditional uniaxial strength theory is not consummate and the multi-axial theory should be adopted. Based on a lot of experiment data and solid mechanics theory, some models are established to reflect the complex material mechanics behavior, such as dilatancy and different behavior in tension and compression, by considering the influence of principle and deviatonic stresses. For concrete, there are Ottosen model, and Chen-Chen model [42–45] as well as the model proposed by Guo and Wang [46]. For rock like material, it is more sensitive to the stress state, and the commonly used model, such as the Mohr-Coulomb model and D-P model, are hardly able to take into account the influence of stress state on failure. In order to reveal the failure mechanism, the quasi triaxial and true triaxial experiments have been used to investigate the change of strength and frictional angle under different confining pressures, and some complex multi-axial strength models have been presented [47–49]. Xiao et al. [50,51] investigated the existing constitutive models and proposed a unified constitutive model for both isotropy and anisotropy conditions, and applied it to the analysis of granular soil.

Besides the stress criterion, the strain criterion is also used in the failure mechanism researches of concrete and rock [52]. In addition, energy, which can reflect both stress and strain at the same time, has the advantage of global representation and is better for revealing the failure of material. Xie et al. [53] studied the damage of rock with the energy method, and the energy variation tendency in the local failure process.

(ii) Study on local damage based on damage mechanics theory. Damage mechanics as a newly branch of solid mechanics was developed during the 1960s. With either a continuous damage scalar variable or damage field variable, some subtle defects in material are reflected, and then the evolutionary process and the effects of the defects on the material mechanical behavior under loading can be studied [54,55]. Both concrete and rock are heterogeneous material essentially, in which there are a lot of defects and micro-cracks. With damage variables representing the defects, the failure of dam concrete and foundation rock can be studied more realistically.

With damage mechanics theory, Gunn [56] studied the safety degree of arch dam, and Duan et al. [57] did some research on the failure mechanism of rock excavated relaxation and its influence on the performance of Jinping arch dam. The results showed that the relaxation of foundation following excavation has a negative impact on the performance of the arch dam in general, which would lead to an increase in dam stress in local areas near the relaxation zone. The research disclosed that the decrease extent of elastic modulus in the relaxation zone is the main factor affecting stresses in the dam. Using an anisotropic damage model, Du et al. [58] studied the failure of Dagangshan arch dam under strong earthquake. They pointed out that in the dynamic analysis of arch dam, both of the anisotropic property and the asymmetry characteristic of tension and compression should be taken into account in the damage constitutive model, and the failure of dam is mainly caused by the tension fracture. On the basis of it the dynamic safety of the dam was evaluated. In [59–62], by treating the existing defects or cracks in dam as the structural damage variable, the evolution of these defects and the effects on dam safety were studied. In addition, Lu et al. [63] and Deng et al. [64] also studied the failure of concrete dam under multi-field coupling situation, like seepage-stress coupling and temperature-stress coupling, with the damage mechanics theory. The damage mechanics theory can reveal the fracture and failure mechanism in some extent, but either isotropic or anisotropic damage model treats the material as homogeneous, with which the shape and size of crack in concrete can not be analyzed.

(iii) Study on local damage based on meso-mechanics theory. Both concrete and rock are essentially heterogeneous material. Concrete is a material made up of aggregate, cement mortar and the interface between them. Rock mass is also heterogeneous because of containing some interfaces like joints and fractures, even if the intact rock is made up of types of mineral crystals. Although these ingredients are quite small in size, they affect the material mechanical properties a lot. Since the traditional solid mechanics theory can hardly handle heterogeneous problem, the meso-mechanics theory, a newly established branch of solid mechanics theory, was proposed to analyze the failure mechanism of heterogeneous materials. Using the meso-mechanics theory, the mechanical property and behavior of heterogeneous material can be studied, the initiation and propagation of damage be simulated, and the failure mechanism can be revealed.

Concrete cracking has always been a hot-spot in dam engineering, but the crack initiation and propagation mechanism are still not well understood. With the development of computer and based on the theory of meso-mechanics, some outstanding researchers as Wrigers [65], Cusatis [66], Bazant [67,68] and Leite [69] established several models to study the problem with meso-mechanics theory and uniformization method. The results well disclosed that the initiation of crack is mostly from the interface between the aggregate and mortar, and the aggregate shape and grading as well as cement mortar strength affect a lot on the concrete strength. Du et al. [70] established a numerical concrete model for simulating aggregate with arbitrary shape (Figure 2). Using this model the initiation and propagation of cracks were studied (Figure 3), and the load-displacement curve was obtained, which is quite consistent with the laboratory experiment (Figure 4). Nazari and Riahi [71], Zhu et al. [72,73] and Xu et al. [74] studied the influence of inclusion and imperfect interface on the material macroscopic behavior, which explains the brittle fracture and shear dilatancy of concrete better, and plays a positive role in research of concrete local damage. Mungule [75] and Grassl [76] explored the microscopic structure of concrete containing the interfaces between aggregate and mortar, and presented the influence on the macroscopic property and the fracture process zone (FPZ). In [77], with meso-mechanics method, Wu analyzed the cracking process from microcrack initiation to macroscopic fracture in concrete dam, and evaluated the effect of different location and depth of crack on the dam safety, which were compared with lab model tests.

Both theoretical results and engineering practice have shown that the behavior of foundation rock is greatly affected by structure planes inside the rock. Traditionally, the Mohr-Coulomb criterion is used for failure analysis of the plane, namely shear failure along the plane will happen as the shear stress exceeds the shear strength. The macroscopic mechanical parameters in Mohr-Coulomb criterion, namely the cohesive strength and the frictional angle, are from laboratory tests. According to meso-mechanics it has been revealed that failure of structure plane is affected not only by the mechanical property of filling in plane but also by the geometry, microscopic structure as well as the filling percentage [78,79]. Dui et al. [80–83] developed the basic theory of meso-mechanics. They obtained an explicit theoretical solution of Eshelby tensor for transversely isotropic inclusion; and proposed the meso-mechanics model of multiple medium for analyzing fractured layer rock; established

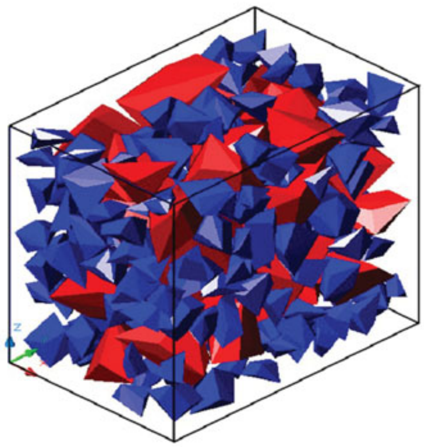

Figure 2 3D random concrete aggregate model.

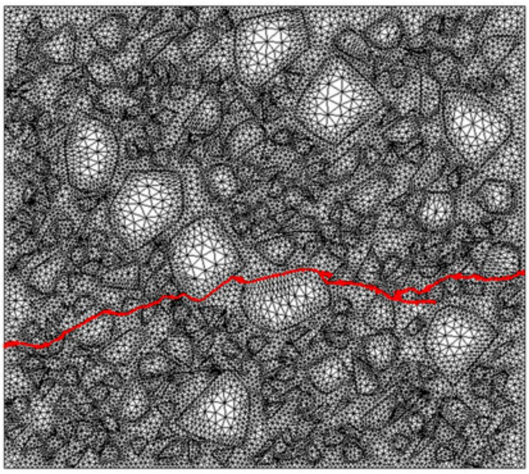

Figure 3 Numerical simulation of concrete cracking.

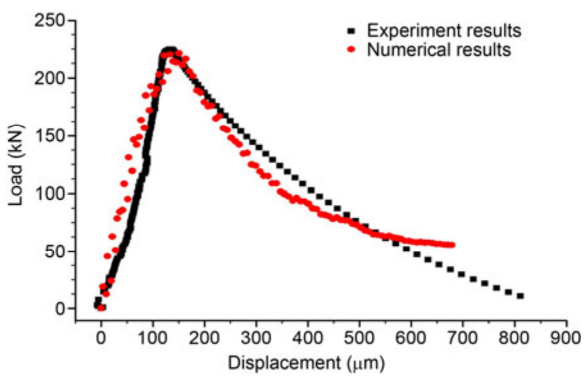

Figure 4 Load-displacement of Jingpin arch dam concrete.

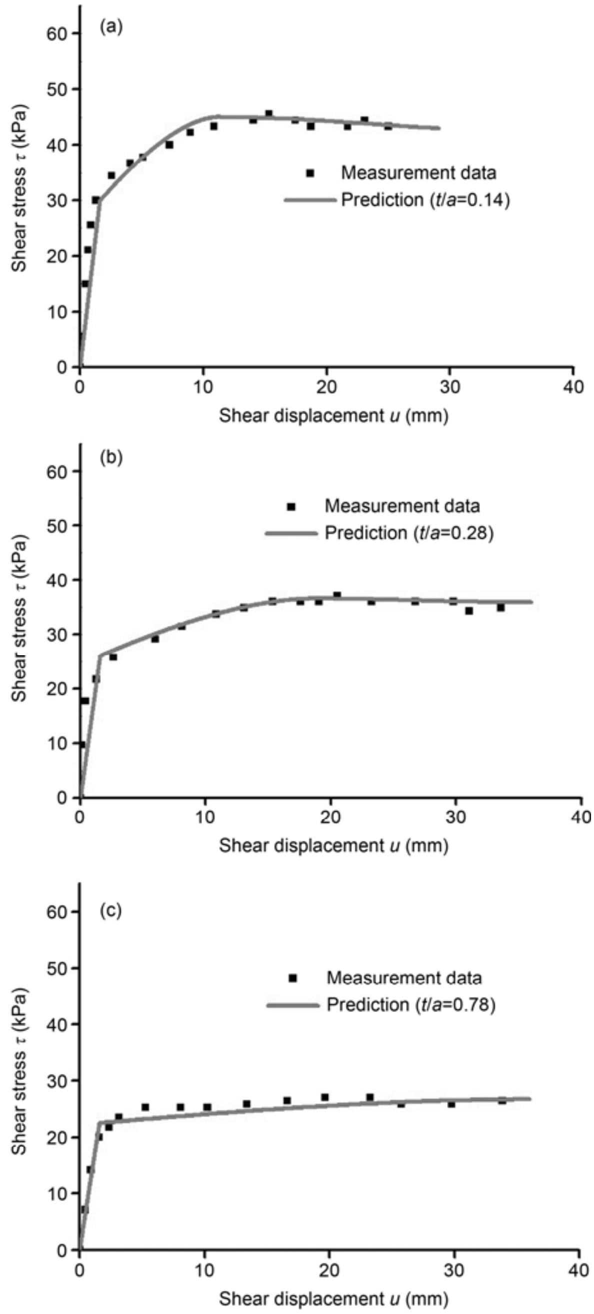

Figure 5 Shear stress-displacement curves with different filling percentages.

several non-linear constitutive models (Figure 5) for structure plane, which can reflect the post-peak softening due to wear of ledges on the plane, the coupling in normal and tangential directions, and the effect of the filling material.

(iv) Local damage and failure research under coupling condition. Temperature variation and seepage are the two mainly factors for local failure of arch dam. After reservoir raised, the existing cracks in dam and the structure planes in foundation rock would become the seepage channels, and the coupling effects of stress-seepage and deterioration of the planes caused by seepage could increase the failure possibility of the arch dam. Chai and Xu [84] and Hu et al. [85] pointed out that seepage is unfavorable for dam global stability, especially the sudden change of water level would cause the variation of seepage field in the foundation rock, which is more like to introduce the local damage in rock foundation. Yang et al. [86] and Huang et al. [87] studied the seepage-stress coupling with meso-mechanics approach and obtained some meaningful results. In [88–92], some approaches were proposed to handle the temperature-seepage-stress coupling problem, and some progresses were obtained both for engineering practice and further research.

3.2 Safety analysis of local strength failure

Strength check is one of the most important parts for the safety evaluation of high arch dam. Besides the multiple arch-cantilever method requested by the dam design codes, many modern numerical methods and tests are developed to obtain more realistic stresses and displacements for static [93–98] and dynamic [99–104] analysis of dam. With these methods and tests, the location and area as well as the extent of cracking, crushing and shear failure can be figured out. Since cracking is the major form of local strength failure for high arch dam, it is becoming more and more important in the content of high arch dam safety evaluation. Currently, there are mainly two kinds of cracking models: smeared crack model and discrete crack model.

(i) Smeared crack model for cracking analysis. Smeared crack model is the most widely used in concrete cracking analysis, in which, the cracks are treated as a series of parallel micro-cracks in the element, and the stiffness deterioration in normal direction of the micro-cracks is used to represent initiation and propagation of the micro-cracks [105].

In engineering practice, finite element method (FEM) is commonly adopted for calculating the maximum principle tensile stress in arch dam and compares the results with the tensile strength of concrete. It is considered that cracking would happen if the calculated maximum principle tensile stress exceeds the tensile strength, and the propagation direction of crack is normal to the maximum principle tensile stress [106,107]. Bazant [108,109] had contributed a lot to the establishment and development of the smeared crack model. He explored the scaling law of FEM mesh and the fracture energy, and presented a method for determining the fracture energy parameter independent from mesh and the optimal mesh size for computing. At present, the smeared crack model has been widely used in the analysis of crack initiation [110], crack stability induced by temperature [60] and crack expansion in long-term operation [59]. In almost all the popular commercial software, such as ABAQUS, ANSYS, and MARC, there is a special module of the smeared crack model.

The recently developed peri-dynamics theory is also capable of analyzing material failures. Huang et al. [111] applied the PD method to failure process analysis of concrete, which can display initiation and propagation of the crack dynamically. But there is still a long way to go to apply it to 3D analysis and actual engineering.

The shortcoming of smeared crack model is that it only gives a certain range of cracking by elements, while the shape and location of the crack can not be obtained. The discrete crack model could handle the problems.

(ii) Discrete crack model for cracking analysis. Discrete crack model is usually adopted in fracture mechanics method for analyzing initiation and expansion of concrete crack [112–114].

Kaplan [115] first applied the classical fracture mechanics to concrete fracture research in 1961. Since then, a lot of achievements have been made on concrete fracture with fracture mechanics. In 1976, Hillerborg et al. [116] proposed a model called fictitious crack model (FCM) for simulating the cohesive behavior in the fracture process zone (FPZ) in concrete, and the corresponding parameter determination method were also given. The model is based on the fracture mechanics theory and it considers the existing FPZ in the crack tip of concrete, so it could treat the cracking problem more realistically, and is widely welcomed by the researchers. But for this model it is difficult to remesh as the crack propagates. There are usually two ways to overcome the problem. One is by assuming the crack location and direction a prior [117], which, however, is usually not in consistent with realistic situations; the other way is to remesh during each step in the expanding process of the crack [118], which is quite costly in computing time.

Extend finite element method (XFEM) proposed by Belytschko et al. [119,120] can avoid the contradiction between FEM mesh and crack expansion. The method is based on the partition of unity theory proposed by Babuska and Melenk [121] in 1996. By introducing the Heaviside function and the asymptotic displacement fields near the crack tip into the standard FEM shape function, the discontinuous due to crack can be handled with ordinary mesh, and in this way the crack initiation and expansion can be simulated independently of the FEM mesh. Ren et al. [122–127] applied the XFEM approach to the analysis of concrete cracking and hydraulic fracturing, and presented the crack expanding path in dam under loading and the effect of cracks on the dam safety. XFEM is an effective method to analyze crack problem, but the calculation efficiency and programming generalization still need to be studied in the coming years.

Both of the smeared crack model and the discrete crack model have advantages and shortcomings, so the idea of combing the two approaches for concrete cracking will have a promising future [128].

(iii) Crack criterion of concrete. Due to a lot of factors affecting concrete cracking, the different structural performance requirements and working conditions, the definition of cracking is quite different and there are several crack criteria. Generally, the concrete crack criterion can be concluded into strain criterion and stress criterion.

The maximum strain and stress criterion are the most widely used traditional crack criterion. They assume that fracture would happen if the maximum principle stress exceeds the material strength or the maximum principle strain is larger than the allowable value. The criteria are simple and easy to use in practice. The D-P criterion is also a very popular crack criterion used in engineering practice, which can be found in lots of commercial software. But it is also found that the parameter of dilatancy angle ψ has great effects on the cracking area in smeared crack model, and the inconsistency between the dilatancy angle and the frictional angle could cause convergence difficulty.

Due to a lot of unpredictable factors, cracking of concrete dam can hardly be avoided, and there are many cracked dams that are still of good operation. Therefore Ren [129] proposed the idea of allowable cracking in the concrete dam, i.e. cracking in dam concrete is allowed, but the crack should be controlled within a certain width and depth. With the experimental data of concrete under tension, the relations between the tensile strain, crack width and the permeability coefficient were set up, and a cracking criterion based strain was established based on seepage prevention [110]. Because the data of pulling crack of concrete samples are from the foreign literatures [130,131], not from the tests of dam concrete in China, there is a long way to apply it to dams.

In the context of fracture mechanics, the crack initiation and expansion can be figured out according to the stress intensity factor and the fracture energy. Based on a lot of experimental data, Xu et al. [132,133] proposed the double K criterion for concrete crack, and presented the relation between the G-R curve of crack expansion and the material softening regime. The obtained results have been used for restricting crack of both concrete dam and concrete pressure tunnel. Bao et al. [134] obtained the energy distribution near the crack tip when crack expanding by using the comentropy analysis.

There are many local damage criteria at present, but due to the complexity of failure mechanism, the criteria are just a guide in practice. For the heterogeneous material like concrete, the combination of fracture mechanics and meso-mechanics would be a possible approach to analyze the evolution process from micro-crack initiation, nucleation to macro-crack formation, which can be called the multi-scale approach. But a lot of work is needed to be done to achieve the goal.

3.3 Preventive measures of local damage

Many factors would cause local damage in high arch dam [61,63,135,136], especially cracking. From dam shape design, foundation excavation and reinforcement, concrete pouring and temperature control to loading action, all of these affect the cracking of concrete. A lot of work has been done on cracking prevention and control by engineers and researchers.

The shape design of high arch affects not only the global stability but also the local stress state. It has been proved [137–139] that the optimization of dam shape would reduce the high stress area in dam body and decrease the maximum value of stresses, which could reduce the possibility of dam cracking.

The pouring scheme and the corresponding temperature control are the key measures for cracking prevention. Zhong et al. [140–142] conducted some research on the order of pour by pour and the temperature control scheme of dam concrete to predict the maximum temperature during the pouring process. The obtained achievements have been used in practice.

Crack detection and monitoring are also important issues for safety control of arch dam. Fu et al. [143] studied the possible cracking of Xiaowan high arch dam under temperature-stress coupling action according to the monitoring data, which can provide the scientific basis for cracking prevention. Besides, Bao et al. [144,145] and Gu et al. [146] studied the variation of existing crack in dam and gave some advises for dam safety. And the researches of Liu et al. [147] and Lei et al. [148] on monitoring of crack initiation and expansion were from microscopic and macroscopic views respectively. The problem is that the fine crack can not be detected in present, so it is difficult to verify the above methods.

4 Conclusions

Arch dam has a good mechanical behavior, but due to the huge water pressure and high stress level in dam, complex topographic and geologic conditions, formidable environment and high intensity earthquake, there is still a risk of failure. The failure of high arch dam has two levels: the local damage at material level and the global destruction at structure level. Ren had summarized the recent research advances in global safety of high arch dam in [35,37], including the slip of the abutment rock, the destabilization of arch dam along its base surface and the global destruction of high arch dam. The research advance in the local damage and failure risk of high arch dam are focused in this paper, as the supplements for safety research of high arch dam.

The failure risk research of high arch dam was reviewed, and the model used for identifying the dam failure risk factors was presented with the priority order of risk factors. Accordingly, the major risk sources of high dam failure were identified as the foundation deterioration and strong earthquake. Using the fault tree method, the failure mode and failure probability of high arch dams were introduced, and the principle for determining failure mode of high arch dam and the calculation method of failure probability were briefed. Meanwhile, the determination principle of acceptable risk standard for high arch dam was presented, and the acceptable risk rate and the acceptable standard value of various risk loss were given.

It is pointed out that the local damage belongs to strength failure at the material level. The study on the local failure mechanism of arch dam is reviewed, based on the theory that is from traditional strength theory to damage mechanics and meso-mechanics theory. Aiming at the cracking, the main pattern of local failure of high arch dams, the research advance in the analysis methods and cracking criteria for smeared crack model and discrete crack model are summarized, and the research findings of preventive measures for local failure are shown.

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